Final Report for the

VEHICLE FOR SPACE TRANSFER AND RECOVERY (VSTAR)

VOLUME II

SUBSTANTIATING ANALYSES AND DATA

A design project by students in the Department of Aerospace Engineering at Auburn University, Auburn, Alabama, under the sponsorship of NASA/USRA Advanced Design Program.

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Auburn, Alabama
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A	-	area	ft^2
A_{tank}	-	surface area of fuel tank	ft^2
a	-	acceleration	ft /sec^2
a	-	semimajor axis	ft
a_{max}	-	maximum acceleration	ft / sec^2
a_{min}	-	minimum acceleration	ft / sec^2
F	-	force	lbf
g	-	value of acceleration due to gravity at earth's surface	ft / sec^2
g_c	-	gravitational constant	lbm/lbf ft/sec^2
h	-	height	ft
h	-	altitude from surface of the earth	ft
h_{vapor}	-	heat of vaporization of fuel	BTU/lbm
ISP	-	ISP of engine	sec
K_{insul}	-	conductivity of insulation	BTU in./ft^2 rankine
l	-	length	ft
m	-	mass	lbm
m_{air}	-	mass of air in the cabin	lbm
m_{brnout}	-	mass of vehicle at burnout	lbm
m_{cabin}	-	mass of cabin	lbm
$m_{cargo\ module}$	-	mass of cargo module	lbm
m_{crew}	-	mass of crew members	lbm
$m_{dot\ fuel}$	-	mass flow rate of propellents	lbm/sec
m_{evap}	-	mass of fuel that evaporates	lbm
m_{fuel}	-	mass of fuel required for given ΔV	lbm
m_{insul}	-	mass of insulation	lbm

$m_{initial}$ -	mass of vehicle at begining of burn	lbm
$m_{life\ support}$ -	mass of life support systems	lbm
m_{pay} -	mass of payload	lbm
$m_{shielding}$ -	mass of meteorite shielding	lbm
$m_{structure}$ -	mass of structure of the cabin	lbm
$m_{support\ structure}$ -	mass of the support structure for the fuel tanks	lbm
m_{tank} -	mass of fuel tank	lbm
m_{total} -	total mass of vehicle including fuel	lbm
n -	number of crew members	-
o -	stress	psi
o_{max} -	maximum allowable stress in a material	psi
p_{bottom} -	pressure at bottom of tank	psi
p_{fuel} -	vapor pressure of fuel	psi
p_{vapor} -	vapor pressure of fuel	psi
Q_{dot} -	rate of heat leak into fuel tank	BTU/hour
Q_{total} -	total heat leak into fuel tank	BTU
R -	mass ratio	-
r -	altitude from earth's center	ft
r -	density	lbm/ft^3
r_{fuel} -	density of fuel	lbm/ft^3
r_{insul} -	density of insulation	lbm/ft^3
r_{metal} -	density of metal in structure	lbm/ft^3
$r_{metal\ in\ tank}$ -	density of metal in tank	lbm/ft^3
r_{tank} -	radius of fuel tank	ft
t -	time	hr, min, sec
t -	time of burn	seconds
t_{insul} -	thickness of insulation	inches

T_{end}	-	endurance of mission	hours
Thrust	-	engine thrust	lbf
T_{in}	-	inside temperature of fuel tank	rankine
T_{out}	-	outside temperature of fuel tank	rankine
V	-	velocity	ft/sec
$V_{metal\ in\ tank}$	-	volume of metal in fuel tank	ft^3
V_{tank}	-	volume of fuel tank	ft^3
$v_{exhaust}$	-	effective exhaust velocity	ft/sec
ΔV	-	change in velocity	ft/sec
μ	-	gravitational mass parameter for earth	ft^3/sec^2

INTRODUCTION

This document contains reference materials, calculations, and trade studies used in the analysis and selection of VSTAR components. The document is organized by each major VSTAR system each of which contains material pertinent to that system. Many sections contain simple graphs and tables used to make qualitative comparisons of various VSTAR component candidates. Equations and/or calculations used for a particular analysis are also included where applicable.

Mission Plans

ΔV ANALYSIS

SLR Mission

This analysis determines the impulse maneuvers required for executing LEO to GEO Hohmann transfers for the SLR mission. Two possible methods of transfer are considered for this orbit change. The first ΔV calculation applies to the LEO-GEO transfer involving the transfer from LEO to a high-earth orbit followed by a plane change to place the vehicle in geosynchronous orbit. The total ΔV required for the method 1 transfer is found to be approximately 18,040 ft/sec. The second calculation is for a LEO-GEO transfer in which the orbital plane change is executed by a two-impulse maneuver within the altitude change. The total ΔV required for the method 2 transfer is found to be approximately 14,271 ft/sec.

IVA Mission

This analysis determines the impulse maneuvers required for executing the 53.27° plane change in low-earth orbit (28.5° Space Station inclination plus 23.27° Earth inclination relative to the ecliptic plane). The total ΔV required for the constant orbit plane change is approximately 22,504 ft/sec.

The calculations associated with this analysis assume a low-earth orbit altitude of 230 miles and a high-earth orbit altitude of 22,000 miles. Derivation of equations used in ΔV calculations is given in (Ref. 4).

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ΔV CALCULATIONS

I. SLR MISSION

LEO Altitude: $h_{LEO} = 230$ mi.

HEO/GEO Altitude: $h_{HEO} = h_{GEO} = 22{,}000$ mi

Gravitational Parameter: $\mu_E = 1.470646882 \times 10^{16}$ ft^3/s^2

1. LEO-GEO Transfer (Plane Change at HEO)

a. LEO-HEO Hohmann

$$r_{LEO} = r_e + h_{LEO} = 22{,}140{,}096 \text{ ft}$$

$$r_{HEO} = r_e + h_{HEO} = 137{,}085{,}696 \text{ ft}$$

* Assume circular orbit ($a_{LEO} = r_{LEO}$, $a_{HEO} = r_{LEO}$)

$$V_{LEO} = V_1 = \sqrt{\frac{\mu_E}{r_{LEO}}} = 25{,}773.97 \text{ ft/s}$$

$$V_{HEO} = V_2 = \sqrt{\frac{\mu_E}{r_{HEO}}} = 10{,}357.58 \text{ ft/s}$$

Transfer Ellispe

$$a_T = \frac{1}{2}(r_{LEO} + r_{HEO}) = 79{,}612{,}896 \text{ ft}$$

Speed at Perigee

$$V_{T_1} = \left[\mu_E\left(\frac{2}{r_{LEO}} - \frac{1}{a_T}\right)\right]^{1/2} = 33{,}819.63 \text{ ft/s}$$

Speed at Apogee

$$V_{T_2} = \left[\mu_E\left(\frac{2}{r_{HEO}} - \frac{1}{a_T}\right)\right]^{1/2} = 5{,}462.06 \text{ ft/s}$$

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$$\Delta V_1 = V_{T_1} - V_1 = 8{,}045.66 \text{ ft/s}$$

$$\Delta V_2 = V_2 - V_{T_2} = 4{,}895.52 \text{ ft/s}$$

$$\underline{\Delta V_{Hohmann}} = \Delta V_1 + \Delta V_2 = \underline{12{,}941.18 \text{ ft/s}}$$

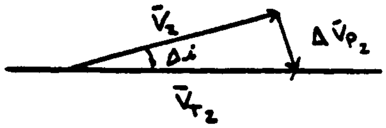
Time of Transfer :

$$t_T = \frac{1}{2}\left(2\pi\sqrt{\frac{a_T^3}{\mu_e}}\right) = 18{,}402.24\,s = 5.11 \text{ hours}$$

b. <u>HEO - GEO Plane Change</u> (One-Impulse)

$$V_{T_2} = V_2$$

$$\Delta i = 28.5°$$



$$\Delta V_{P_2} = \left[V_2^2 + V_{T_2}^2 - 2V_2V_{T_2}\cos\Delta i\right]^{1/2}$$

$$= \underline{5{,}099.10 \text{ ft/s}}$$

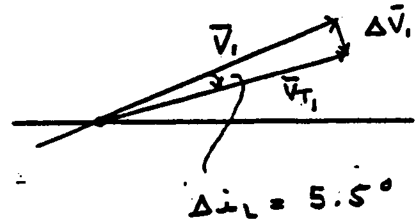
$$\Delta V_{TOTAL} = \Delta V_{Hohmann} + \Delta V_{P_2}$$

$$\underline{\Delta V_{TOTAL} = 18{,}040.28 \text{ ft/s}} \quad *$$

2. LEO - GEO Transfer (Two-Impulse Plane Change)

LEO - GEO Hohmann

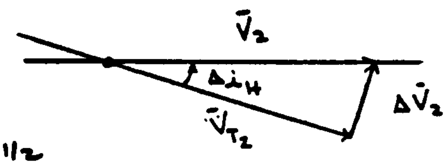
a. Ascending Node



$$\Delta V_1 = \left[V_1^2 + V_{T_1}^2 - 2V_1V_{T_1}\cos\Delta i_L\right]^{1/2}$$

$$\Delta V_1 = 8529.87 \text{ ft/s}$$

b. Descending Node



$$\Delta V_2 = \left[V_2^2 + V_{T_2}^2 - 2V_2V_{T_1}\cos i_H\right]^{1/2}$$

$\Delta i_H = 23.0°$

$$\Delta V_2 = 5{,}741.15 \text{ ft/s}$$

$$\Delta V_{TOTAL} = \Delta V_1 + \Delta V_2$$

$$\underline{\Delta V_{TOTAL} = 14{,}271.02 \text{ ft/s}} \quad *$$

II. IVA Mission

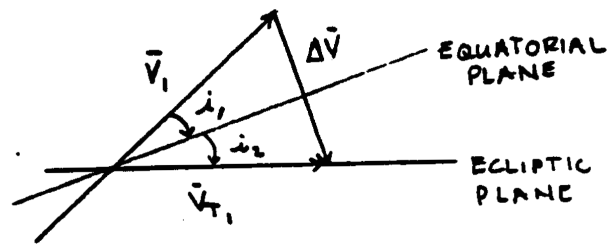
Plane Change at LEO

$r_{LEO} = 22,140,096$ ft

$V_1 = V_{LEO} = 25,773.97$ ft/s

$V_{T_1} = V_1$

$\Delta i = i_1 + i_2 = 51.77°$



$i_1 = 28.5°$ (Space Station inclination)

$i_2 = 23.27°$ (Earth's inclination)

$$\Delta V_1 = \left[V_1^2 + V_{T_1}^2 - 2V_1V_{T_1}\cos\Delta i\right]^{1/2}$$

$\underline{\Delta V_1 = 22,504.09 \text{ ft/s}}$ *

PROPULSION

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Table 1 - Electric Propulsion System Comparisons (Ref. 18)

	Ion	Arcjet	Resistojet	Microwave	MPD arcjet
Adv:	high Isp efficient	simplicity	simplicity highly developed	electrodeless energy efficient	high Isp high thrust
Dis:	complex low thrust high power	electrode-erosion energy losses	temp. limited corrosion	power efficiency	high current electrode-erosion instabilities power losses

Table 2 - Liquid Chemical Rocket Engine Comparisons (Ref. 25)

Rocketdyne Advanced Orbital Transfer Vehicle Engine:

Isp= 492 secs	Engine length (retracted)=1.02 m
Propellant= LH2, LOX	(extended)=3.91 m
Thrust: max=66750 N	Nozzle exit diameter=1.98 m
min=2225 N	Area ratio=1300:1
MR (O/F)= 6.0:1	Engine mass=198 kg

Pratt and Whitney Advanced Orbital Transfer Vehicle Engine:

Isp=486 secs	Engine length (retracted)=1.02 m
Propellant=LH2, LOX	(extended)=3.05 m
Thrust: max=66750 N	Nozzle exit diameter=1.63 m
min=2225 N	Area ratio=640:1
MR(O/F)= 6.0:1	Engine mass=204 kg

Aerojet Advanced Orbital Transfer Vehicle Engine:

Isp=482 secs	Engine length (retracted)=0.98 m
Propellant=LH2, LOX	(extended)=1.96 m
Thrust: max=13350 N	Nozzle exit diameter=0.76 m
min=445 N	Area ratio=1200:1
MR(O/F)= 6.0:1	Engine mass=57 kg

Pratt and Whitney RL-10 Category IV:

Isp=470 secs	Engine length (retracted)=1.45 m
Propellant=LH2,LOX	(extended)=2.90 m
Thrust: max=66730 N	Nozzle exit diameter=1.68 m
min=16688 N	Area ratio=401:125
MR (O/F)= 6.0:1	Engine mass=193 kg

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Table 3 - Dual Fuel / Mixed Mode Rocket Engine Characteristics (Ref. 6)

Parameter	Mode 1 ($LOX/RP\text{-}1/LH_2$)	Both Modes	Mode 2 (LOX/LH_2)
Vacuum Thrust (lbf)	20,000.		9915.
Vacuum Delivered Specific Impulse (sec.)	418.6		460.6
Chamber Pressure (psia)	2000.		1007.
Total Propellant Flowrate (lb/sec)	47.8		21.5
Mixture Ratio	4.25		7.0
Nozzle Area Ratio		400.	
Nozzle Exit Diameter (in.)		49.3	
Engine Length (in.)		61.2/95.2*	
Total Engine Weight (lb.)		557.	

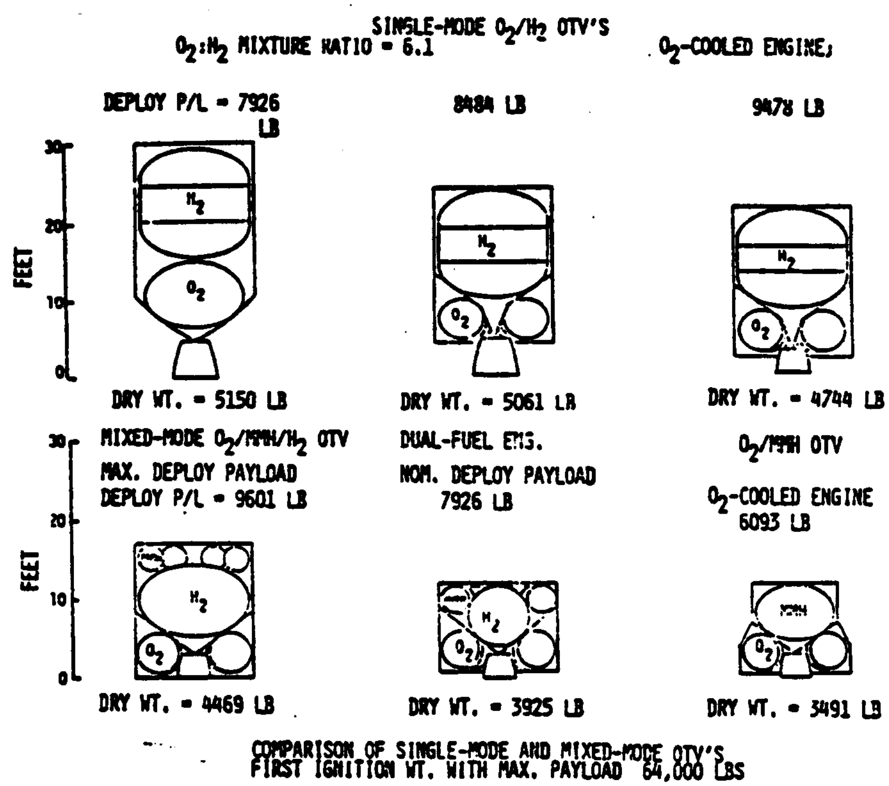

Figure 1 - Single Vs. Mixed Mode OTV Comparisons (Ref. 6)

STRUCTURE

Thermal Protection

The selection of the type of radiator was based on survivability, and the membrane area per Btu/h output. Typically the higher the area required the higher the weight of the device. The estimated survivability was based on research. For VSTAR the heat pipes are to be used as thermal buses between fluid systems and the choice of these based on the same characteristics as the radiator. The data used to determine the ft^2/Btu/h comes from several sources. The Btu/h is converted from Watts and this wattage is the maximum output of the device under choked flow conditions. As can be seen in Table , the best heat pipe for the thermal bus is the axially grooved variable-conductance heat pipe, but as a radiator, it's survivability is far to low. As for the radiator, the rotating bubble membrane radiator is the superior choice as it is highly survivable and does not waste liquid. (Ref. 9, 16 & 31)

Table 4. Radiator and Heat Pump Data

Type	ft^2/Btu/h	Survivability
Osmotic Heat Pipe	0.00293	medium-low
Heat Pipe Sandwich Panel	0.00007	medium
Double Walled Artery Heat Pipe	3.264E-7	medium-low
Axially Grooved Variable-Conductance Heat Pipe	1.310E-8	medium
RBMR	0.00019	high
Liquid Droplet Radiator	NA *	medium-high
Heat Pipe as Radiator (ave)	0.00075	medium to low

* this device sprays the hot liquid directly into space but would weigh the same as the RMBR before the liquid was used up.

Material Selection

Table 5 shows the stress allowable and density of each material that was considered. The exact cost of each material produced is not known, however, based on research estimated relative costs have been determined. Compatibility is known and is accounted for in the design. The material with the smallest density/stress is the strongest per unit mass. Metals withstand debris and micrometeoroid impact much better than do composites with epoxy bases, because metals tend to buckle before they are punctured and epoxys tend to shatter.

Therefore a metal is preferred for debris protection. Careful consideration of this data with the micrometeoroid protection results in the choices made for the vehicle components. (Ref. 17 & 24)

Table 5. Material Properties (Ref. 24)

material	allowable stress (psi)	density (lbm/in^3)	density/stress	cost
4130 Steel	70000	0.283	4.0428E-6	low
2024 Aluminum	42000	0.100	2.3809E-6	very low
Boron Epoxy	85333	0.072	8.4961E-7	medium
Graphite Epoxy	100000	0.057	5.7000E-7	medium
Aluminum Oxide/ Aluminum	42222	0.100	2.3684E-6	low
Boron Aluminum 2024	100000	0.100	1.00E-6	high
Boron Aluminum 6061	96889	0.100	1.032E-6	high
Graphite Aluminum GY70 2024	37911	0.100	2.638E-6	high
Graphite Aluminum V60054 2024	43156	0.100	2.317E-6	high
Graphite Aluminum T50 2024	31111	0.100	3.214E-6	high

Debris and Micrometeoroid Protection

BUMPER is a program provided to us by NASA/Marshal to determine the chance of penetration of a vessel. BUMPER uses the equations based on some simplifying assumptions and your inputs. There are two modes corresponding to single wall and double wall vessels. For double wall, inputs are surface area, sheild thickness, sheild stand-off distance, vessel thickness, and whether or not MLI is being used. For the single wall surface area, vessel thickness and MLI use is inputted. The program then returns the percented chance of debris or micrometeoroid protection, (Ref. 22).

LIFE SUPPORT

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Table 6 · EC/LSS System Functions (Ref. 10)

ECLSS FUNCTION	MAJOR EQUIPMENT
• ATMOSPHERE PRESSURE & COMPOSITION CONTROL – TOTAL & PARTIAL PRESSURE CONTROL & MONITORING – FIRE DETECTION & SUPPRESSION	PRESSURE REGULATION PORTABLE OXYGEN SYSTEM SMOKE/FIRE DETECTORS FIRE SUPPRESSION SYSTEM
• MODULE TEMPERATURE & HUMIDITY CONTROL	DEHUMIDIFICATION VENTILATION FANS AIR COOLING HEAT EXCHANGERS
• ATMOSPHERE REVITALIZATION – CO_2 CONTROL/REMOVAL/REDUCTION – O_2 & N_2 MAKEUP – TRACE GAS MONITORING & CONTROL	CARBON DIOXIDE REMOVAL AND COLLECTION CARBON DIOXIDE REDUCTION CONTAMINATION CONTROL ODOR CONTROL ATMOSPHERE MONITORING OXYGEN GENERATION EMERGENCY OXYGEN AND NITROGEN STORAGE
• WATER MANAGEMENT – WASTE WATER COLLECTION/PROCESSING – WATER QUALITY MONITORING – STORATE & DISTRIBUTION OF RECOVERED WATER	EVAPORATION PURIFICATION WATER QUALITY MONITORING WATER STORAGE
• WASTE MANAGEMENT – COLLECT/PROCESS URINE – COLLECT/STORE FECAL MATTER	WASTE COLLECTION AND STORAGE EMERGENCY WASTE COLLECTION HOT/COLD WATER SUPPLY
• EVA SUPPORT – PROVIDE EXPENDABLES/SUPPORT TO EMU & MMU – PROVIDE LIFE SUPPORT SERVICES TO AIRLOCK/HYPERBARIC FACILITY	SUITS AND BACKPACKS RECHARGE STATIONS AIR LOCK SUPPORT

Table 7 · EC/LSS Performance Requirements (Ref. 10)

PARAMETER	UNITS	OPERATIONAL	DEGRADED (1)
CO_2 PARTIAL PRESS	MMHG	3.0 MAX	7.6 MAX
TEMPERATURE	DEG F	65–75	60–85
DEW POINT (2)	DEG F	40–60	35–70
POTABLE WATER	LB/MAN–DAY	6.8–8.1	6.8 (3)
HYGIENE WATER	LB/MAN–DAY	12 (3)	6 (3)
WASH WATER	LB/MAN–DAY	28 (3)	14 (3)
VENTILATION	FT/MIN	15–40	10–100
O_2 PARTIAL PRESSURE (4)	PSIA	2.7–3.2	2.4–3.8
TOTAL PRESSURE (5)	PSIA	10.2 OR 14.7	10.2 OR 14.7
DILUTE GAS	——	N_2	N_2
TRACE CONTAMINANTS (8)	MG/M^3	TBD	TBD
MICRO–ORGANISMS	CFU/M^3 (6)	500 (7)	750 (7)

NOTES:

(1) DEGRADED LEVELS MEET "FAIL OPERATIONAL" CRITERIA.
(2) RELATIVE HUMIDITY SHALL BE WITHIN THE RANGE OF 25–75 PERCENT.
(3) MINIMUM.
(4) IN NO CASE SHALL THE O_2 PARTIAL PRESSURE BE BELOW 2.3 PSIA, OR THE O_2 CONCENTRATION EXCEED 25.9 PERCENT OF THE TOTAL PRESSURE AT 14.7 PSIA OR 30 PERCENT OF THE TOTAL PRESSURE AT 10.2.
(5) ALL SYSTEMS SHALL BE COMPATIBLE WITH BOTH 10.2 AND 14.7 PSIA TOTAL PRESSURE.
(6) CFU – COLONY FORMING UNITS.
(7) THESE VALUES REFLECT A LIMITED BASE. NO WIDELY SANCTIONED STANDARDS ARE AVAILABLE.
(8) BASED ON NHB 8060.1B, (J6400003).

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Table 8 - EC/LSS Average Design Loads (Ref. 10)

- METABOLIC O_2	1.84 LB/MAN DAY
- LEAKAGE AIR	5.00 LB/DAY TOTAL
- EVA O_2	1.22 LB/8 HR EVA
- EVA CO_2	1.48 LB/8 HR EVA
- METABOLIC CO_2	2.20 LB/MAN DAY
- DRINK H_2O	4.09 LB/MAN DAY
- FOOD PREPARATION H_2O	1.58 LB/MAN DAY
- METABOLIC H_2O PRODUCTION	0.76 LB/MAN DAY
- CLOTHS WASH H_2O	27.50 LB/MAN DAY
- HAND WASH H_2O	4.00 LB/MAN DAY
- SHOWER H_2O	8.00 LB/MAN DAY
- EVA H_2O	9.68 LB/8 HR EVA
- PERSPIRATION AND RESPIRATION H_2O	4.02 LB/MAN DAY
- URINAL FLUSH H_2O	1.09 LB/MAN DAY
- URINE H_2O	3.31 LB/MAN DAY
- FOOD SOLIDS	1.36 LB/MAN DAY
- FOOD H_2O	1.00 LB/MAN DAY
- FOOD PACKAGING	1.00 LB/MAN DAY
- URINE SOLIDS	0.13 LB/MAN DAY
- FECAL SOLIDS	0.07 LB/MAN DAY
- SWEAT SOLIDS	0.04 LB/MAN DAY
- EVA WASTEWATER	2.00 LB/8 HR EVA
- CHARCOAL REQUIRED	0.13 LB/MAN DAY
- METABOLIC SENSIBLE HEAT	7000 BTU/MAN DAY
- HYGIENE LATENT H_2O	0.96 LB/MAN DAY
- FOOD PREPARATION LATENT H_2O	0.06 LB/MAN DAY
- LAUNDRY LATENT H_2O	0.13 LB/MAN DAY
- WASH H_2O SOLIDS	0.44%
- SHOWER/HAND WASH H_2O SOLIDS	0.12%
- AIR LOCK GAS LOSS	1.33 LBS/USE
- TRASH	1.80 LB/MAN DAY
- TRASH VOLUME	0.16 FT^3/MAN DAY

Table 9 - EC/LSS Technology Requirements (Ref. 10)

- FECAL WASTE MANAGEMENT
- TRASH/FOOD MANAGEMENT
- SENSOR DEVELOPMENT
  - MASS GAUGING
  - TRACE GAS
  - AIR/WATER QUALITY
- WATER RECLAMATION/PROCESSING SYSTEMS
- REGENERATIVE CO_2 REMOVAL/REDUCTION SYSTEM
- MARS ATMOSPHERE PROCESSING SYSTEM FOR OXYGEN, NITROGEN & WATER

POWER

FAMILY OF PRIMARY BATTERY CELLS

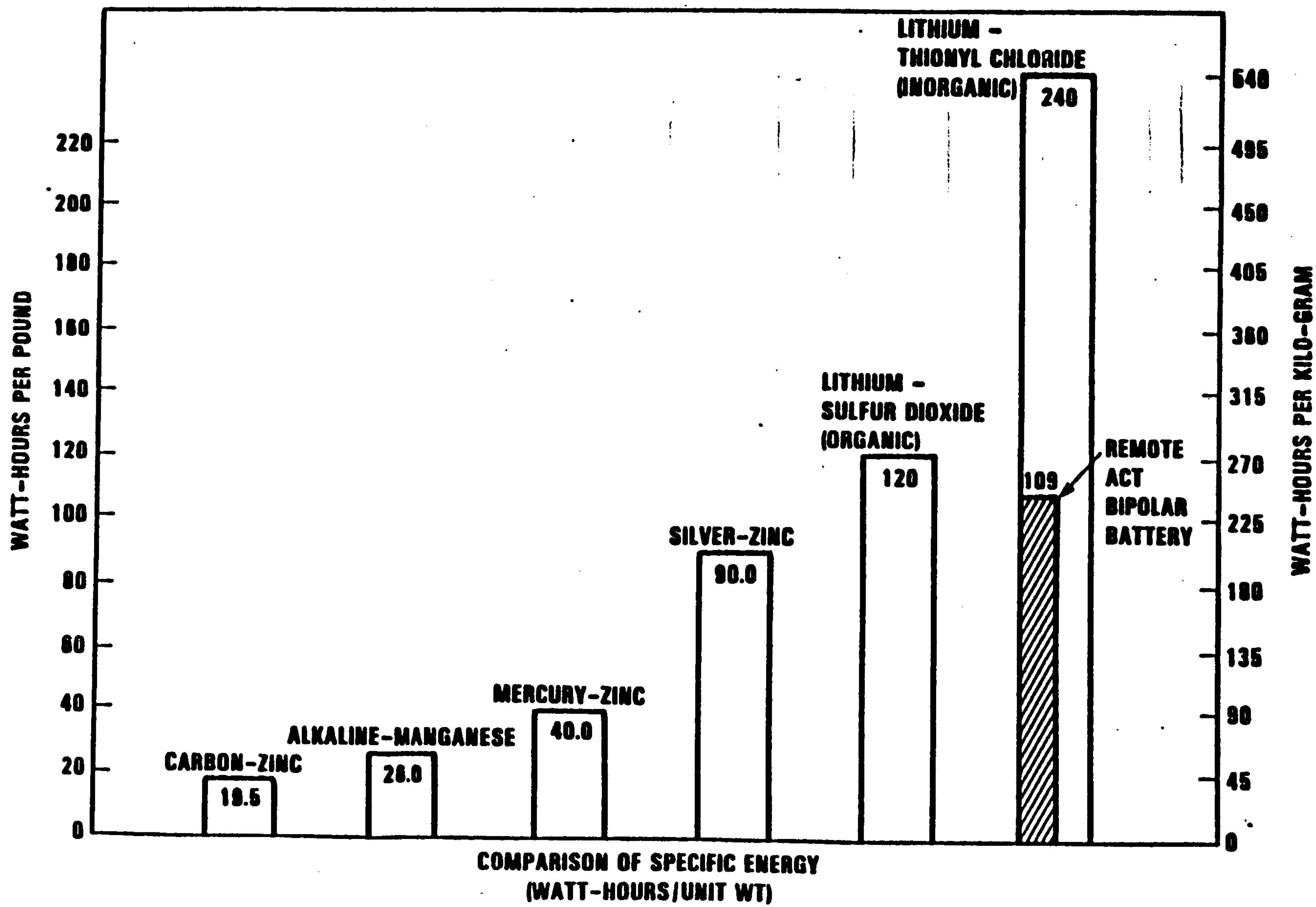

Figure 2 - Family of Primary Battery Cells

COST ANALYSIS

There are several equations required in cost analysis. These equations are given below for each of the subsections, vehicle costs and program management costs. Vehicle costs are in 1978 dollars which must be multipled by 2 to approximate 1988 dollars. The management costs are functions of the vehicle costs. (Ref. 21)

Vehicle Costs

DDT&E

Structural Cost = $(2)(1.8531)(\text{Structural Weight})^{0.491}$

Electrical System Cost = $(2)(0.6000)(\text{Electrical System Weight})^{0.584}$

Propulsion System Cost = $(2)(0.1075)(\text{Propulsion System Weight})^{0.876}$

FH

Structural Cost = $(2)(0.4445)(\text{Structural Weight})^{0.440}$

Electrical System Cost = $(2)(0.0422)(\text{Electrical System Weight})^{0.784}$

Propulsion System Cost = $(2)(0.1158)(\text{Propulsion System Weight})^{0.550}$

Management Costs

Integration, Assembly & Checkout

DDT&E = $9.1208(\text{STE})^{0.461}$

FH = $(\text{Total FH})^{0.832}$

System Test and Evaluation

DDT&E = $13.101(\text{Total FH})^{0.672}$

FH is zero. It is accounted for in cost of operation.

Systems Engineering & Integration

$$DDT\&E = 0.4519(DISG)^{0.876}$$

$$FH = 0.3750(\text{Total FH})^{0.855}$$

Program Management

$$DDT\&E = 0.6952(DISGS)^{0.731}$$

$$FH = 0.3146(FIS)^{0.798}$$

Suplementary Equations

$$STE = 11.232(\text{Total FH})^{0.672}$$

DISG = Total DDT&E + Integ., Assem. & Check (DDT&E) + Sys. Test & Eval. (DDT&E)

DISGS = STE + Total DDT&E + Integ., Assem. & Check (DDT&E) + Sys. Eng. & Integ. (DDT&E)

FIS = Total FH + Integ., Assem. & Check (FH) + Sys. Eng. & Eval. (FH)

OPTIMIZATION

Optimization Methods

The following describes the derivation and assumptions made for each of the mathematical expressions describing the calculated parameters. The analysis is based on a division of the configuration into the components shown in Figure 3.

The mass of components in many cases are the sum of the masses of the subcomponents. Their derivations are discussed under the appropriate sections and are not repeated here.

Calculation of m_{cabin} : The mass of the cabin is constant and not dependent on the acceleration loads during flight. This is justified by assuming that it will be launched in one piece from the space shuttle and will necessarily encounter higher accelerations during launch than those experienced for a typical mission.

$$
\begin{aligned}
m_{cabin} &= m_{crew} + m_{air} + m_{structure} + m_{shielding} + m_{other} \\
&= 600 + 150 + 1140 + 157 + 200 \\
&= 2247
\end{aligned}
$$

Calculation for $m_{life\ support}$: The mass of the life support system includes the mass of the power supply system and is equal to a base mass plus the mass of the consumables (breathing oxygen, water, etc) used per hour by the crew.

$$
\begin{aligned}
m_{life\ support} &= f(\#\ \text{of crew}, T_{end}) \\
&= 1075 + 1.39\ n\ T_{end}
\end{aligned}
$$

Calculation of $m_{cargo\ module}$: The mass of the cargo module is dependent upon the mass of structures above it which it will have to accelerate during thrusting periods, as shown in Figure 5

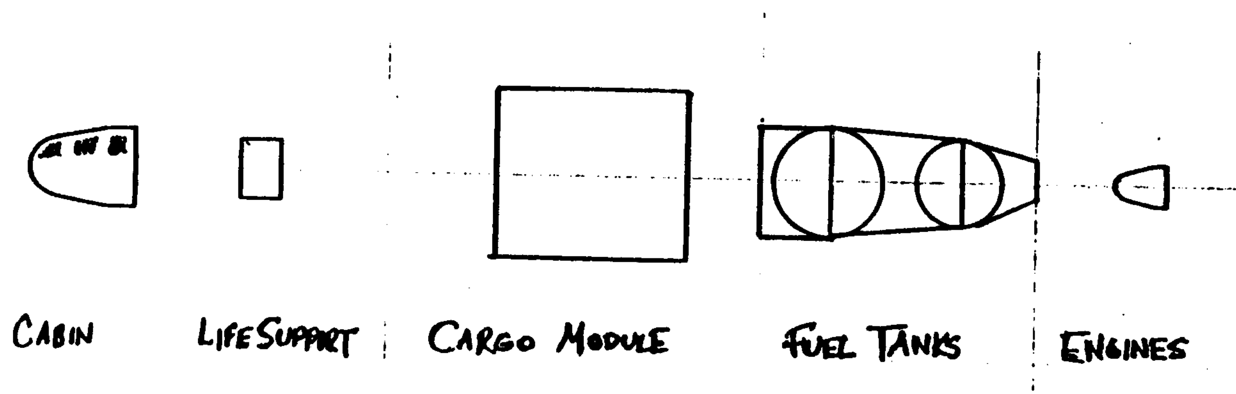

Figure 3. Idealized Components for Analysis Purposes

$$m_{cargo\ module} = f(m_{cabin}, m_{life\ support}, m_{pay}, a_{max})$$

An approximate function for the mass can be developed by considering Figure 4.

Let A be the cross sectional area of a column of density, r, and maximum allowable stress, o, and length l. The material must withstand the stress generated from mass m and acceleration a. The force exerted on the column is :

$$F = m\,a$$

and is equal :

$$F = A\,o$$

Equating and solving for A gives :

$$A = m\,a / o$$

The mass of the column is then :

$$m_{column} = A\,l\,r$$
$$= r\,l\,m\,a / o \qquad \ldots\ldots \quad (1)$$

This equation is based on the assumption that the mass of the column does not contribute any to the stresses in it. This is a reasonable assumption if $m >> m_{column}$.

An extrapolation can be made from the column of Figure 6 to the proposed truss structure of the cargo module in Figure 5 if the additional assumptions are made :

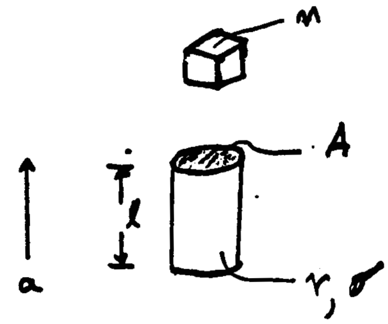

Figure 4 - Stress in a Column

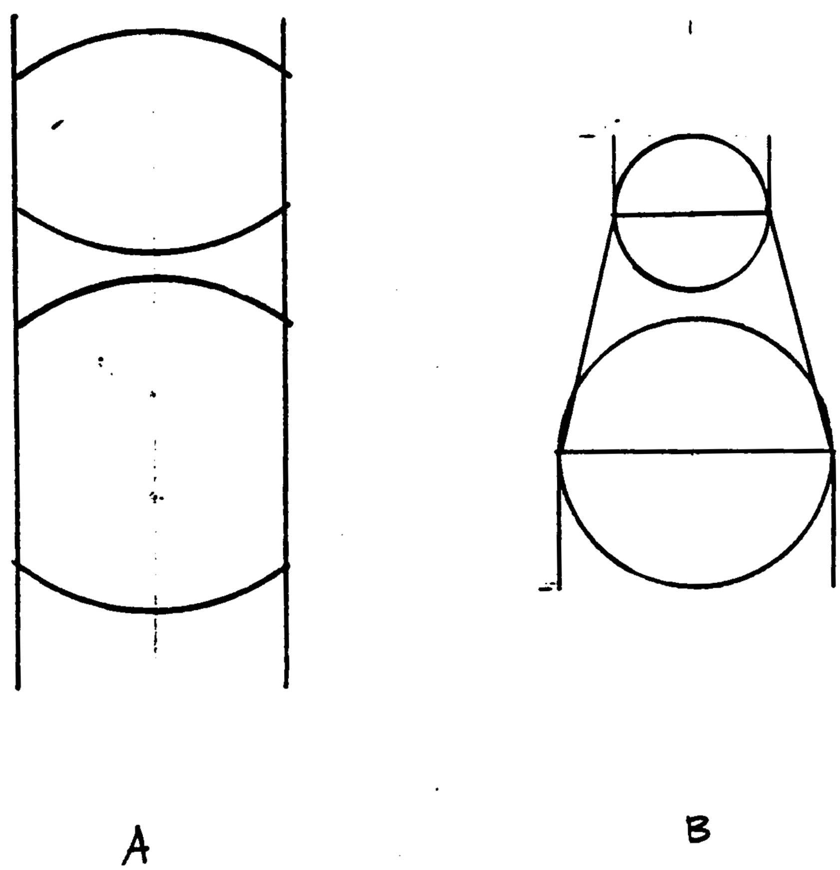

Figure 5 - Two Possible Tank Configurations

1) The cross sectional area is equal to the sum of the cross sectional areas of the constituent members of the structure.

2) The maximum allowable stress in the supporting members is much lower than the compression yield stress to account for lower buckling stresses in a slender column.

3) The effective density is higher than the actual density to account for the presence of cross beams and diagonal members which do not bear the compressive loads.

Typical r/o values for steel and aluminum are 3.8×10^{-6} and 2.9×10^{-6} [lbm in /lbf], respectively. For Aluminum with the maximum allowable stress to be 1/10 the compressive yield stress, the effective density to be 3 times the actual density, and a length of 20 feet, the following expression results:

$$m_{support\ structure} = 0.017\ m\ a_{max}$$

Including an approximate value for the mass of the metiorite shielding gives :

$$m_{support\ structure} = 150 + 0.017\ m\ a_{max}$$

Where :

$$m = m_{cabin} + m_{life\ support} + m_{pay}$$

Calculation of m_{tank} : Two possible configurations for the arrangement of the fuel tanks are shown in figure 5.

The tanks in Figure 5A are of equal radii, but because of different volume requirements they are of different lengths. They employ a monocoque structure which resists internal pressure and the forces due to acceleration and the mass above it. Figure 7B shows two spherical tanks with

a seperate support structue for resisting the acceleration loads. The tanks in Figure 7A are efficient in that they provide a dual role in resisting the internal pressure and the loads due to acceleration. However, the nonsherical geometry is inefficient in providing a light tank for a given volume. Additionally, the monocoque skirt between the two tanks will provide an excellent path for heat conduction between the two tanks at different temperatures, which if carrying LO_2 and LH_2 will be over 100 degrees rankine difference. This will complicate thermal control of the two tanks and increase boiloff losses. The arrangement of Figure 7B was chosen because it allows the use of spherical tanks which weigh less for a given tank volume, and since they are not actively involved in resisting the acceleration loads, they can be more completley thermally isolated.

The mass of the tank can be expressed in the following form :

$$m_{tank} = f(\, m_{fuel}, r_{fuel}, m_{evap}, p_{fuel}, a_{min}, r_{metal})$$

The required volume is given by :

$$v_{tank} = (m_{fuel} + m_{evap}) \,/\, r_{fuel}$$

The radius is given by :

$$r_{tank} = (\, 3\, v_{tank} \,/\, 4\, pi\,)^{1/3}$$

From fluid statics the pressure of a liquid of density, r, under an acceleration, a, at a depth of h is :

$$p = p_0 + r\, a\, h$$

Applying this to a spherical fuel tank.:

$$p_{bottom} = p_{vapor} + 2\, r_{fuel}\, A_{min}\, r_{tank}$$

It can be shown that for a constant thrust, the greatest pressure will occur at the bottom of the fully filled fuel tank even though the acceleration is at a minimum. Assuming a thin walled pressure vessel the thickness required is:

$$t_{tank} = p_{bottom}\, r_{tank} / 2\, o$$

The area is :

$$A_{tank} = 4\, \pi\, r_{tank}^{\ 2}$$

The volume of metal in the tank is :

$$v_{metal\ in\ tank} = A_{tank}\, t_{tank}$$

And the mass of the tank is :

$$m_{tank} = v_{metal\ in\ tank}\, r_{metal}$$

Calculation of m_{evap}: The fuels are cryogenic and are assumed to be continually receiving a heat input which holds them at the boiling point for a given pressure. Any heat input is used in vaporizing the liquid into its gaseous state, which is immediatly vented, thus keeping the pressure constant.

The particular insulation chosen conducts heat thirty times faster in the direction parallel to the layers than in the direction perpendicular to the layers. It will be assumed that the heat received from radiation on the illuminated side of the tank will be conducted to the unilluminated side allowing an average surface temperature T_{out} to be used in the below equations.

It is assumed that this is the only source of heat input into the tanks for the entire mission. This is not true however since there will be a radiated and conducted heat transfer during the firing of the engines due to the fuel tanks being in close proximity to the hot engine and exhaust plume. These calculations may be dependent on many variables, but only the heat due to the radiation on the illuminated side of the tank is considered in the following calculation.

The heat leak rate into the tank is given by :

$$Q_{dot} = k_{insul} A_{tank} (t_{out} - t_{in}) / t_{insul}$$

Then the total heat leak is simply :

$$Q_{total} = Q_{dot} T_{end}$$

And the mass evaporated is :

$$m_{evap} = Q_{total} / h_{vapor}$$

Calculation of m_{insul} : The insulation is assumed constant thickness and covers the entire spherical tank.

$$m_{insul} = r_{insul} A_{tank} t_{insul}$$

Calculation of $m_{support\ structure}$: The equation for the mass of the support structure is developed along the same lines as $m_{cargo\ module}$. It is assumed to be of the form :

$$m_{support\ structure} = 200 + 0.017\ m\ a_{max}$$

Where :

$$m = m_{cabin} + m_{life\ support} + m_{pay} + m_{tank}$$

200 – approximate mass of meteroite shielding

Calculation of m_{engine} : The mass of the engines are assumed to be known for a given configuration and are taken from the avaliable literature.

Calculation of m_{brnout} and m_{total} : The burnout mass is simply the sum of all the masses calculated above. The total mass is the sum of the burnout mass and the mass of the fuel.

Calculation of a_{max} and a_{min} : The thrust is assumed constant over the burn time. By assuming specific thrust vs. time profiles, the maximum accelerations could be reduced while still allowing relatively short burn times, however, here it is assumed they are constant.

The accelerations then are simply :

$$a_{max} = Thrust / m_{brnout}$$

$$a_{min} = Thrust / m_{total}$$

Calculation of mass ratio : It is assumed their will be no losses due to gravitational and drag effects. The mass ratio required then for a given ΔV and ISP is :

$$R = e^{\Delta V / g\,ISP}$$

Calculation of m_{fuel} :

From the definition of mass ratio:

$$R = (m_{brnout} + m_{fuel}) / m_{brnout}$$

Solving for m_{fuel} gives :

$$m_{fuel} = m_{brnout} (R - 1)$$

There is one other assumption made in the program that needs to be pointed out. The boiloff occurs before the engines ignite. This results in a higher mass ratio than actually needed since in reality the boiloff would occur continually and some of the fuel mass would not be imparted the full 29,000 ft/sec ΔV.

Calculation of burn times:

For a given ΔV:

$$m_{final} = m_{initial}\, e^{-\Delta V / g\,ISP}$$

The mass of the fuel used is:

$$m_{fuel} = m_{initial} - m_{final}$$

The thrust can be expressed as:

$$Thrust = m_{dot\ fuel} V_{exhaust}$$

Since the values in the above equation are constant:

$$Thrust = m_{fuel}\, g\, ISP / t$$

Solving for t:

$$t = m_{fuel}\, g\, ISP / Thrust$$

Correctina for units:

$$t = m_{fuel}\, g\, ISP / Thrust\, g_e$$

$$t = m_{fuel}\, ISP / Thrust$$

The program listing and program runs are included below. Following this are graphs showing data on the liquid hydrogen and liguid oxygen as used in the program.

OPTIMIZATION PROGRAM OUTPUT

OXYGEN/HYDROGEN RATIO	[.]	:	7
OXYGEN/RPJ RATIO	[.]	:	4.25
ISP	[.]	:	420
ACCELERATION - MAX.	[g's]	:	2.42
ACCELERATION - MIN.	[g's]	:	0.28
DELTA V - OBTAINABLE	[ft/sec]	:	29000
MASS RATIO	[.]	:	8.536368
STUCTUAL COEFF.	[.]	:	0.0733
PAYLOAD COEFFICIENT	[.]	:	0.0496
TIME, ENDURANCE	[hours]	:	72
THRUST	[lbf]	:	30000

MASSES OF COMPONENTS :

CABIN	[lbm]	:	2247
LIFE SUPPORT MODULE	[lbm]	:	1376.86
CARGO MODULE	[lbm]	:	504.8966
CARGO	[lbm]	:	5000
SUPPORT STRUCTURE	[lbm]	:	642.4102
HYDROGEN TANK	[lbm]	:	936.6639
OXYGEN TANK	[lbm]	:	448.6059
RPJ TANK	[lbm]	:	74.83677
ENGINE	[lbm]	:	1000
TOTAL BURNOUT MASS	[lbm]	:	12392.82
MASS OF FUEL	[lbm]	:	93396.84
TOTAL MASS	[lbm]	:	105789.7

				HYDROGEN	OXYGEN	RPJ
TANK	- MASS	[lbm]	:	936.66	448.61	74.84
	- MAX. STRESS	[lbf/in^2]	:	35000.00	35000.00	35000.00
	- METAL DNSTY	[lbm/ft^3]	:	489.00	489.00	489.00
	- PRESS., BOT.	[lbf/in^2]	:	20.14	21.67	21.28
	- RADIUS	[ft]	:	8.09	6.18	3.42
	- SURFACE AREA	[ft^2]	:	822.78	479.65	147.12
	- THICKNESS	[in]	:	0.0279	0.0230	0.0125
	- VOLUME	[ft^3]	:	2219.22	987.80	167.79
	- VOLUME, MTL	[ft^3]	:	1.92	0.92	0.15
PROP.	- VAPOR PRS	[lbf/in^2]	:	20.00	20.00	20.00
	- DENSITY	[lbm/ft^3]	:	4.38	68.64	95.11
	- MASS	[lbm]	:	9681.38	67769.66	15945.80
	- TEMP.	[rankine]	:	38.38	166.41	58.33
	- HEAT.VAPRZ	[btu/lbm]	:	188.16	91.62	100.00
SURFACE TEMPERATUE		[rankine]	:	600.00	600.00	600.00
INSULATION	- RHO	[lbm/ft^2-in]	:	0.20	0.20	0.20
	- MASS	[lbm]	:	41.14	23.98	7.36
	- THCKNS	[in]	:	0.25	0.25	0.25
	-K	[btu-in/hr-ft^2]	:	0.000056	0.000056	0.000056
HEAT LEAK	- RATE	[btu/hour]	:	103.51	46.59	17.85
	- TOT	[btu]	:	7452.54	3354.22	1285.23
MASS EVAPORATED		[lbm]	:	39.61	36.61	12.85

OXYGEN/HYDROGEN RATIO	[.]	:	7
ISP	[.]	:	460
ACCELERATION - MAX.	[g's]	:	2.45
ACCELERATION - MIN.	[g's]	:	0.35
DELTA V - OBTAINABLE	[ft/sec]	:	29000
MASS RATIO	[.]	:	7.084234
STUCTUAL COEFF.	[.]	:	0.0887
PAYLOAD COEFFICIENT	[.]	:	0.0611
TIME, ENDURANCE	[hours]	:	72
THRUST	[lbf]	:	30000

MASSES OF COMPONENTS :			
CABIN	[lbm]	:	2247
LIFE SUPPORT MODULE	[lbm]	:	1376.86
CARGO MODULE	[lbm]	:	508.9224
CARGO	[lbm]	:	5000
SUPPORT STRUCTURE	[lbm]	:	641.6741
HYDROGEN TANK	[lbm]	:	902.9588
OXYGEN TANK	[lbm]	:	438.6012
ENGINE	[lbm]	:	1000
TOTAL BURNOUT MASS	[lbm]	:	12253.81
MASS OF FUEL	[lbm]	:	74555.06
TOTAL MASS	[lbm]	:	86808.88

				HYDROGEN	OXYGEN
TANK	- MASS	[lbm]	:	902.96	438.60
	- MAX. STRESS	[lbf/in^2]	:	35000.00	35000.00
	- METAL DNSTY	[lbm/ft^3]	:	489.00	489.00
	- PRESS.,BOT.	[lbf/in^2]	:	20.17	22.01
	- RADIUS	[ft]	:	7.99	6.10
	- SURFACE AREA	[ft^2]	:	802.17	467.62
	- THICKNESS	[in]	:	0.0276	0.0230
	- VOLUME	[ft^3]	:	2136.36	950.87
	- VOLUME, MTL	[ft^3]	:	1.85	0.90
PROP.	- VAPOR PRS	[lbf/in^2]	:	20.00	20.00
	- DENSITY	[lbm/ft^3]	:	4.38	68.64
	- MASS	[lbm]	:	9319.38	65235.68
	- TEMP.	[rankine]	:	38.38	166.41
	- HEAT.VAPRZ	[btu/lbm]	:	188.16	91.62
SURFACE TEMPERATUE		[rankine]	:	600.00	600.00
INSULATION	- RHO	[lbm/ft^2-in]	:	0.20	0.20
	- MASS	[lbm]	:	40.11	23.38
	- THCKNS	[in]	:	0.25	0.25
	-K	[btu-in/hr-ft^2]	:	0.000056	0.000056
HEAT LEAK	- RATE	[btu/hour]	:	100.91	45.42
	- TOT	[btu]	:	7265.84	3270.10
MASS EVAPORATED		[lbm]	:	38.62	35.69

OXYGEN/HYDROGEN RATIO	[.]	:	6
ISP	[.]	:	470
ACCELERATION - MAX.	[g's]	:	2.44
ACCELERATION - MIN.	[g's]	:	0.36
DELTA V - OBTAINABLE	[ft/sec]	:	28999.99
MASS RATIO	[.]	:	6.795188
STUCTUAL COEFF.	[.]	:	0.0930
PAYLOAD COEFFICIENT	[.]	:	0.0636
TIME, ENDURANCE	[hours]	:	72
THRUST	[lbf]	:	30000

MASSES OF COMPONENTS :

CABIN	[lbm]	:	2247
LIFE SUPPORT MODULE	[lbm]	:	1376.86
CARGO MODULE	[lbm]	:	507.1932
CARGO	[lbm]	:	5000
SUPPORT STRUCTURE	[lbm]	:	641.9901
HYDROGEN TANK	[lbm]	:	988.1334
OXYGEN TANK	[lbm]	:	411.8053
RPJ TANK	[lbm]	:	3.70943E-08
ENGINE	[lbm]	:	1000
TOTAL BURNOUT MASS	[lbm]	:	12313.14
MASS OF FUEL	[lbm]	:	71356.95
TOTAL MASS	[lbm]	:	83670.09

				HYDROGEN	OXYGEN
TANK	- MASS	[lbm]	:	988.13	411.81
	- MAX. STRESS	[lbf/in^2]	:	35000.00	35000.00
	- METAL DNSTY	[lbm/ft^3]	:	489.00	489.00
	- PRESS., BOT.	[lbf/in^2]	:	20.18	22.04
	- RADIUS	[ft]	:	8.23	5.97
	- SURFACE AREA	[ft^2]	:	851.53	447.96
	- THICKNESS	[in]	:	0.0285	0.0226
	- VOLUME	[ft^3]	:	2336.53	891.52
	- VOLUME, MTL	[ft^3]	:	2.02	0.84
PROP.	- VAPOR PRS	[lbf/in^2]	:	20.00	20.00
	- DENSITY	[lbm/ft^3]	:	4.38	68.64
	- MASS	[lbm]	:	10193.85	61163.10
	- TEMP.	[rankine]	:	38.38	166.41
	- HEAT. VAPRZ	[btu/lbm]	:	188.16	91.62
SURFACE TEMPERATUE		[rankine]	:	600.00	600.00
INSULATION	- RHO	[lbm/ft^2-in]	:	0.20	0.20
	- MASS	[lbm]	:	42.58	22.40
	- THCKNS	[in]	:	0.25	0.25
	-K	[btu-in/hr-ft^2]	:	0.000056	0.000056
HEAT LEAK	- RATE	[btu/hour]	:	107.12	43.51
	- TOT	[btu]	:	7712.90	3132.57
MASS EVAPORATED		[lbm]	:	40.99	34.19

OXYGEN/HYDROGEN RATIO	[.]	:	6
ISP	[.]	:	486
ACCELERATION - MAX.	[g's]	:	2.46
ACCELERATION - MIN.	[g's]	:	0.39
DELTA V - OBTAINABLE	[ft/sec]	:	29000
MASS RATIO	[.]	:	6.379754
STUCTUAL COEFF.	[.]	:	0.0988
PAYLOAD COEFFICIENT	[.]	:	0.0687
TIME, ENDURANCE	[hours]	:	72
THRUST	[lbf]	:	30000

MASSES OF COMPONENTS :			
CABIN	[lbm]	:	2247
LIFE SUPPORT MODULE	[lbm]	:	1376.86
CARGO MODULE	[lbm]	:	510.5695
CARGO	[lbm]	:	5000
SUPPORT STRUCTURE	[lbm]	:	641.3731
HYDROGEN TANK	[lbm]	:	909.1804
OXYGEN TANK	[lbm]	:	380.309
ENGINE	[lbm]	:	1000
TOTAL BURNOUT MASS	[lbm]	:	12197.84
MASS OF FUEL	[lbm]	:	65621.38
TOTAL MASS	[lbm]	:	77819.22

				HYDROGEN	OXYGEN
TANK	- MASS	[lbm]	:	909.18	380.31
	- MAX. STRESS	[lbf/in^2]	:	35000.00	35000.00
	- METAL DNSTY	[lbm/ft^3]	:	489.00	489.00
	- PRESS., BOT.	[lbf/in^2]	:	20.19	22.13
	- RADIUS	[ft]	:	8.01	5.81
	- SURFACE AREA	[ft^2]	:	805.32	423.62
	- THICKNESS	[in]	:	0.0277	0.0220
	- VOLUME	[ft^3]	:	2148.97	819.87
	- VOLUME, MTL	[ft^3]	:	1.86	0.78
PROP.	- VAPOR PRS	[lbf/in^2]	:	20.00	20.00
	- DENSITY	[lbm/ft^3]	:	4.38	68.64
	- MASS	[lbm]	:	9374.48	56246.90
	- TEMP.	[rankine]	:	38.38	166.41
	- HEAT. VAPRZ	[btu/lbm]	:	188.16	91.62
SURFACE TEMPERATUE		[rankine]	:	600.00	600.00
INSULATION	- RHO	[lbm/ft^2-in]	:	0.20	0.20
	- MASS	[lbm]	:	40.27	21.18
	- THCKNS	[in]	:	0.25	0.25
	-K	[btu-in/hr-ft^2]	:	0.000056	0.000056
HEAT LEAK	- RATE	[btu/hour]	:	101.31	41.14
	- TOT	[btu]	:	7294.41	2962.40
MASS EVAPORATED		[lbm]	:	38.77	32.33

VSTAR Optimization Program

```
10 GOSUB 1000 'INITIALIZE VARIABLES
20 CLS:INPUT"OPTION 1 OR 2 ";IJOB
30 ON IJOB GOTO 40,210
40 OPEN"O",#1,"ROCKET1.DAT"
50 FOR CONFIG=1 TO 6
60 READ OXH,OXRP,ISP
70 TEND=72
80 THRUST=30000
90 TINSUL(1)=.25
100 TINSUL(2)=.25
110 TINSUL(3)=.25
120 PVAPOR(1)=20
130 PVAPOR(2)=20
140 PVAPOR(3)=20
150 GOSUB 2000
160 GOSUB 3000 'GET MFUEL
170 PRINT#1,OXH,OXRP,ISP,TEND,THRUST,TINSUL(1),TINSUL(2),TINSUL(3),PVAPOR(1),
POR(2),PVAPOR(3),MFUEL
175 PRINT OXH,OXRP,ISP,TEND,THRUST,TINSUL(1),TINSUL(2),TINSUL(3),PVAPOR(1),PV
R(2),PVAPOR(3) MFUEL
180 NEXT CONFIG
190 CLOSE#1
200 STOP
210 GOSUB 7000 ' SORT DATA
220 OPEN"O",#1,"ROCKET3.DAT"
230 OPEN"I",#2,"ROCKET2.DAT"
240 INPUT#2,OXH,OXRP,ISP,TEND,THRUST,TINSUL(1),TINSUL(2),TINSUL(3),PVAPOR(1)
POR(2),PVAPOR(3),MFUEL
250 GOSUB 2000 ' GET FUEL PROPERTIES
260 GOSUB 3000 ' GET PARAMETERS
270 GOSUB 4000 ' PRINT PARAMETERS
280 IF EOF(2)=0 THEN 240
290 CLOSE
300 STOP
```

```
1000 ' ******************** INITIALIZE CONSTANTS
1005 DIM AREA(3),HVAPOR(3),MEVAP(3),MAXSTRS(3),MTANK(3),PA(3),PTEMP(3),PVAPOR(
,QDOT(3),QTOT(3),RADIUS(3),RFUEL(3),RINSUL(3),RMETAL(3),TANK$(3),TINSUL(3),TOU
3)
1010 DELTAVO=29000!
1020 KINSUL(1)=.000056
1030 KINSUL(2)=.000056
1040 KINSUL(3)=.000056
1080 MAXSTRS(1)=35000!
1090 MAXSTRS(2)=35000!
1100 MAXSTRS(3)=35000!
1110 MPAY=5000
1120 PI=3.1415927#
1130 RMETAL(1)=489
1140 RMETAL(2)=489
1150 RMETAL(3)=489
1160 RINSUL(1)=.2
1170 RINSUL(2)=.2
1180 RINSUL(3)=.2
1190 TANK$(1)="HYDROGEN"
1200 TANK$(2)="OXYGEN"
1210 TANK$(3)="RPJ"
1220 TOUT(1)=600
1230 TOUT(2)=600
1240 TOUT(3)=600
1250 DIM N(3,3)
1260 FOR X=1 TO 3:FOR Y=1 TO 3:READ N(X,Y):NEXT Y:NEXT X
1270 DATA 8,10,6
1280 DATA 10,3,2
1290 DATA 3,3,2
1300 DIM THVAPOR(3,6),HVAPOR1(3,6),PFUEL(3,10),TPFUEL(3,10),RFUEL1(3,10),TRFUE
3,10)
1310 FOR X=1 TO 3
1320 FOR Y=1 TO N(X,1):READ PFUEL(X,Y),TPFUEL(X,Y):NEXT Y
1330 FOR Y=1 TO N(X,2):READ RFUEL1(X,Y),TRFUEL(X,Y):NEXT Y
1340 FOR Y=1 TO N(X,3):READ THVAPOR(X,Y),HVAPOR1(X,Y):NEXT Y
1350 NEXT X
1360 RETURN
1370 DATA 1.044,25.07,1.102,25.27,2.959,28.67,6.689,32.27,13.066,35.87,22.992,
.47,29.446,41.27,33.903,42.37
1380 DATA 4.71,26.87,4.61,30.47,4.48,34.07,4.43,37.67,4.18,41.27,3.99,45.27,3.
,48.47,3.5,52.07,3.14,55.67,2.22,59.27
1390 DATA 32.27,898.83,35.87,860.16,39.79,804.12,43.4,744.19,47,674.61,50.6,59
22
1400 DATA .027,98.67,.035,116.67,2.102,134.67,8.225,152.67,23.655,170.67,78.75
197.67,196.692,224.67,322.342,242.67,501.725,260.87,611.814,269.67
1410 DATA 85.65,97.77,71.2,162.77,.2766,263.67
1420 DATA 10,91.62,500,91.62
1430 DATA 10,35,11,35,12,35
1440 DATA 75,38,75,42,75,46
1450 DATA 20,100,70,100
1460 DATA 7,2.21,460
1470 DATA 7,1000000000000000000,460
1480 DATA 7,4.25,420
1490 DATA 6,1000000000000000000,492
1500 DATA 6,1000000000000000000,486
1510 DATA 6,1000000000000000000,470
```

```
2000 '******************** GET FUEL DENSITIES
2010 FOR X=1 TO 3
2020 FOR Y=1 TO N(X,1)
2030 IF PVAPOR(X)<PFUEL(X,Y) THEN 2050
2040 NEXT Y
2050 PTEMP(X)=TPFUEL(X,Y-1)+(TPFUEL(X,Y)-TPFUEL(X,Y-1))*(PVAPOR(X)-PFUEL(X,Y-1)
/(PFUEL(X,Y)-PFUEL(X,Y-1))
2060 FOR Y=1 TO N(X,2)
2070 IF PTEMP(X)< TRFUEL(X,Y) THEN 2090
2080 NEXT Y
2090 RFUEL(X)=RFUEL1(X,Y-1)+(RFUEL1(X,Y)-RFUEL1(X,Y-1))*(PTEMP(X)-TRFUEL(X,Y-1)
/(TRFUEL(X,Y)-TRFUEL(X,Y-1))
2100 FOR Y=1 TO N(X,3)
2110 IF PTEMP(X)< THVAPOR(X,Y) THEN 2130
2120 NEXT Y
2130 HVAPOR(X)=HVAPOR1(X,Y-1)+(HVAPOR1(X,Y)-HVAPOR1(X,Y-1))*(PTEMP(X)-THVAPOR(X
Y-1))/(THVAPOR(X,Y)-THVAPOR(X,Y-1))
2140 NEXT X
2150 HVAPOR(1)=HVAPOR(1)/RFUEL(1)
2160 RETURN
```

```
3000 '******************** FIND CABIN MASS
3010 MBRNOUT=0
3020 MCABIN=600+150+157+1140+100+100
3030 MBRNOUT=MCABIN
3040 '******************** FIND LIFE SUPPORT SYSTEM MASS
3050 MLIFSUP=1075+(33.54/24)*3*TEND
3060 MBRNOUT=MBRNOUT+MLIFSUP+MPAY
3070 '******************** FIND CARGO MODULE MASS
3080 MCRGMOD=150+.017*MBRNOUT*AMAX
3090 MBRNOUT=MBRNOUT+MCRGMOD
3100 '********************* FIND TANK MASSES
3110 MFUEL(1)=MFUEL/(1+OXH+OXH/OXRP)
3120 MFUEL(2)=MFUEL(1)*OXH
3130 MFUEL(3)=MFUEL(2)/OXRP
3140 FOR X=1 TO 3
3150 MEVAP=0
3160 VTANK(X)=(MFUEL(X)+MEVAP(X))/RFUEL(X)
3170 RADIUS(X)=(3*VTANK(X)/PI/4)^(1/3)
3180 AREA(X)=4*PI*RADIUS(X)^2
3190 PA(X)=PVAPOR(X)+(RFUEL(X)/12^3)*AMIN*(2*RADIUS(X)*12)
3200 TA(X)=PA(X)*RADIUS(X)*12/2/MAXSTRS(X)
3210 T(X)=TA(X)
3220 VMETAL(X)=AREA(X)*T(X)/12
3230 MTANK(X)=VMETAL(X)*RMETAL(X)
3240 QDOT(X)=KINSUL(X)*AREA(X)*(TOUT(X)-PTEMP(X))/TINSUL(X)
3250 QTOT(X)=QDOT(X)*TEND
3260 'PRINT USING"####.####";MEVAP,MEVAP(X)
3280 MEVAP(X)=QTOT(X)/HVAPOR(X)
3290 IF ABS(MEVAP-MEVAP(X))>.01 THEN MEVAP=MEVAP(X):GOTO 3160
3300 MINSUL(X)=RINSUL(X)*AREA(X)*TINSUL(X)
3310 MBRNOUT=MBRNOUT+MTANK(X)+MINSUL(X)+MEVAP(X)
3320 NEXT X
3330 '********************* FIND SUPPORT STRUCTURE MASS
3340 MSUPSTR=200+.017*MBRNOUT*AMAX
3350 MBRNOUT=MBRNOUT+MSUPSTR
3360 '********************* FIND ENGINE MASS
3370 MENGINE=1000
3380 '********************* FIND BURNOUT MASS
3390 MBRNOUT=MBRNOUT+MENGINE
3400 MTOTAL=MBRNOUT+MFUEL
3410 AMAX=THRUST/MBRNOUT
3420 AMIN=THRUST/MTOTAL
3430 'PRINT USING"#####.####";AMAX,AMIN,AC
3440 IF ABS(AMAX-AC)>.01 THEN AC=AMAX:GOTO 3000
3450 MRATIO=2.7182818#^(DELTAVO/32.2/ISP)
3460 MFUEL1=MBRNOUT*(MRATIO-1)
3470 'PRINT USING"##########.##";MFUEL1;MFUEL;MRATIO
3480 IF ABS(MFUEL1-MFUEL)>.01 THEN MFUEL=MFUEL1:GOTO 3000
3490 MRATIO=MTOTAL/MBRNOUT
3500 DELTAV=32.2*ISP*LOG(MRATIO)
3510 EPSILON=(MBRNOUT-MPAY)/(MTOTAL-MPAY)
3520 LAMBDA=MPAY/(MTOTAL-MPAY)
3530 RETURN
```

```
4000 PRINT#1,"OXYGEN/HYDROGEN RATIO [/]        :";OXH
4010 PRINT#1,"OXYGEN/RPJ RATIO      [.]        :";OXRP
4020 PRINT#1,"ISP                   [.]        :";ISP
4030 PRINT#1,"ACCELERATION - MAX.   [g's]      :";:PRINT#1,USING"##.##";AMAX
4040 PRINT#1,"ACCELERATION - MIN.   [g's]      :";:PRINT#1,USING"##.##";AMIN
4050 PRINT#1,"DELTA V - OBTAINABLE  [ft/sec]   :";DELTAV
4060 PRINT#1,"MASS RATIO            [.]        :";MRATIO
4070 PRINT#1,"STUCTUAL COEFF.       [.]        :";:PRINT#1,USING"##.####";EPSIL
4080 PRINT#1!"PAYLOAD COEFFICIENT   [.]        :";PRINT#1,USING"##.####";LAMBDA
4090 PRINT#1,"TIME, ENDURANCE       [hours]    :";TEND
4100 PRINT#1,"THRUST                [lbf]      :";THRUST
4110 PRINT#1,"MASSES OF COMPONENTS :"
4120 PRINT#1," CABIN                [lbm]      :";MCABIN
4130 PRINT#1," LIFE SUPPORT MODULE  [lbm]      :";MLIFSUP
4140 PRINT#1," CARGO MODULE         [lbm]      :";MCRGMOD
4150 PRINT#1," CARGO                [lbm]      :";MPAY
4160 PRINT#1," SUPPORT STRUCTURE    [lbm]      :";MSUPSTR
4170 PRINT#1," HYDROGEN TANK        [lbm]      :";MTANK(1)
4180 PRINT#1," OXYGEN TANK          [lbm]      :";MTANK(2)
4190 PRINT#1," RPJ TANK             [lbm]      :";MTANK(3)
4200 PRINT#1," ENGINE               [lbm]      :";MENGINE
4210 PRINT#1,"TOTAL BURNOUT MASS    [lbm]      :";MBRNOUT
4220 PRINT#1,"MASS OF FUEL          [lbm]      :";MFUEL
4230 PRINT#1,"TOTAL MASS            [lbm]      :";MTOTAL
```

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```
5000 PRINT#1,TAB(25);"TANK #    ";TANK$(1),TANK$(2),TANK$(3)
5010 PRINT#1,"TANK  - MASS             [lbm]          :";:PRINT#1,USING "##########.##"
ANK(1),MTANK(2),MTANK(3)
5020 PRINT#1,"        - MAX. STRESS [lbf/in^2]:";:PRINT#1,USING"##########.##";
STRS(1),MAXSTRS(2),MAXSTRS(3)
5030 PRINT#1,"        - METAL DNSTY [lbm/ft^3]:";:PRINT#1,USING"##########.##";
TAL(1),RMETAL(2),RMETAL(3)
5040 PRINT#1,"        - PRESS., BOT. [lbf/in^2]:";:PRINT#1,USING"##########.##";
1),PA(2),PA(3)
5050 PRINT#1,"        - RADIUS      [ft]        :";:PRINT#1,USING"##########.##";
IUS(1),RADIUS(2),RADIUS(3)
5060 PRINT#1,"        - SURFACE AREA [ft^2]     :";:PRINT#1,USING"##########.##";
A(1),AREA(2),AREA(3)
5070 PRINT#1,"        - THICKNESS   [in]        :";:PRINT#1,USING"########.####"
(1),T(2),T(3)
5080 PRINT#1,"        - VOLUME      [ft^3]      :";:PRINT#1,USING"##########.##";
NK(1),VTANK(2),VTANK(3)
5090 PRINT#1,"        - VOLUME, MTL [ft^3]      :";:PRINT#1,USING"##########.##";
TAL(1),VMETAL(2),VMETAL(3)
5100 PRINT#1," PROP.- VAPOR PRS   [lbf/in^2]:";:PRINT#1,USING"##########.##";
POR(1),PVAPOR(2),PVAPOR(3)
5110 PRINT#1,"        - DENSITY     [lbm/ft^3]:";:PRINT#1,USING"##########.##";
EL(1),RFUEL(2),RFUEL(3)
5120 PRINT#1,"        - MASS        [lbm]       :";:PRINT#1,USING"##########.##";
EL(1),MFUEL(2),MFUEL(3)
5130 PRINT#1,"        - TEMP.       [rankine] :";:PRINT#1,USING"##########.##";
MP(1),PTEMP(2),PTEMP(3)
5140 PRINT#1,"        - HEAT.VAPRZ  [btu/lbm] :";:PRINT#1,USING"##########.##";
POR(1),HVAPOR(2),HVAPOR(3)
5150 PRINT#1,"SURFACE TEMPERATUE  [rankine] :";:PRINT#1,USING"##########.##";
T(1),TOUT(2),TOUT(3)
5160 PRINT#1,"INSULATION - RHO [lbm/ft^2-in]:";:PRINT#1,USING"##########.##";
SUL(1),RINSUL(2),RINSUL(3)
5170 PRINT#1,"            - MASS    [lbm]       :";:PRINT#1,USING"##########.##";
SUL(1),MINSUL(2),MINSUL(3)
5180 PRINT#1,"            - THCKNS [in]         :";:PRINT#1,USING"##########.##";
SUL(1),TINSUL(2),TINSUL(3)
5190 PRINT#1,"           -K [btu-in/hr-ft^2]:";:PRINT#1,USING"######.######";
SUL(1),KINSUL(2),KINSUL(3)
5200 PRINT#1," HEAT LEAK - RATE   [btu/hour]:";:PRINT#1,USING"##########.##";
T(1),QDOT(2),QDOT(3)
5210 PRINT#1,"            - TOT     [btu]       :";:PRINT#1,USING"##########.##";
T(1),QTOT(2),QTOT(3)
5220 PRINT#1," MASS EVAPORATED    [lbm]       :";:PRINT#1,USING"##########.##";M
AP(1),MEVAP(2),MEVAP(3)
```

```
6000 MANV$(1)="INJECT HOMMAN TRANSFER/"
6010 MANV$(2)="CIRCULARIZE          "
6020 MANV$(3)="DE-CIRCULARIZE       "
6030 MANV$(4)="CIRCULARIZE          "
6040 DELTAV(1)=8529.87
6050 DELTAV(2)=5741.15
6060 DELTAV(3)=5741.15
6070 DELTAV(4)=8529.87
6080 T=MFUEL*ISP/THRUST/60
6090 PRINT#1,"TIME OF BURN [minutes] :";T
6100 MINIT=MTOTAL
6110 PRINT:FOR X=1 TO 4
6120 MFINAL=MINIT*2.72^(-DELTAV(X)/32.2/ISP)
6130 MFUEL=MINIT-MFINAL
6140 T=MFUEL*ISP/THRUST/60
6150 PRINT#1,"       -";MANV$(X);":";T,DELTAV(X)
6160 MINIT=MINIT-MFUEL
6170 NEXT X
6180 FOR X=1 TO 15:PRINT#1,"":NEXT X
6190 RETURN
```

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```
7000 N=600
7010 DIM A(N),B(N),C(N),D(N),E(N),F(N),G(N),H(N),I(N),J(N),K(N),L(N)
7020 OPEN"I",#1,"ROCKET1.DAT"
7030 OPEN"O",#2,"ROCKET2.DAT"
7040 M=1:N=0
7050 N=N+1
7060 INPUT#1,A(N),B(N),C(N),D(N),E(N),F(N),G(N),H(N),I(N),J(N),K(N),L(N)
7070 IF EOF(1)=0 THEN 7050
7080 A=0:FOR X=M TO N
7090 IF D(X) > A THEN A=L(X):Y=X
7100 NEXT X
7110 A1=A(M):B1=B(M):C1=C(M):D1=D(M):E1=E(M):F1=F(M):G1=G(M):H1=H(M):I1=I(M):
J(M):K1=K(M):L1=L(M)
7120 A(M)=A(Y):B(M)=B(Y):C(M)=C(Y):D(M)=D(Y):E(M)=E(Y):F(M)=F(Y):G(M)=G(Y):H(
H(Y):I(M)=I(Y):J(M)=J(Y):K(M)=K(Y):L(M)=L(Y)
7130 A(Y)=A1:B(Y)=B1:C(Y)=C1:D(Y)=D1:E(Y)=E1:F(Y)=F1:G(Y)=G1:H(Y)=H1:I(Y)=I1:
)=J1:K(Y)=K1:L(Y)=L1
7140 'PRINT   A(M),B(M),C(M),D(M),E(M)
7150 PRINT#2,A(M),B(M),C(M),D(M),E(M),F(M),G(M),H(M),I(M),J(M),K(M),L(M)
7160 M=M+1
7170 IF M<=N THEN 7080
7180 CLOSE
7190 RETURN
```

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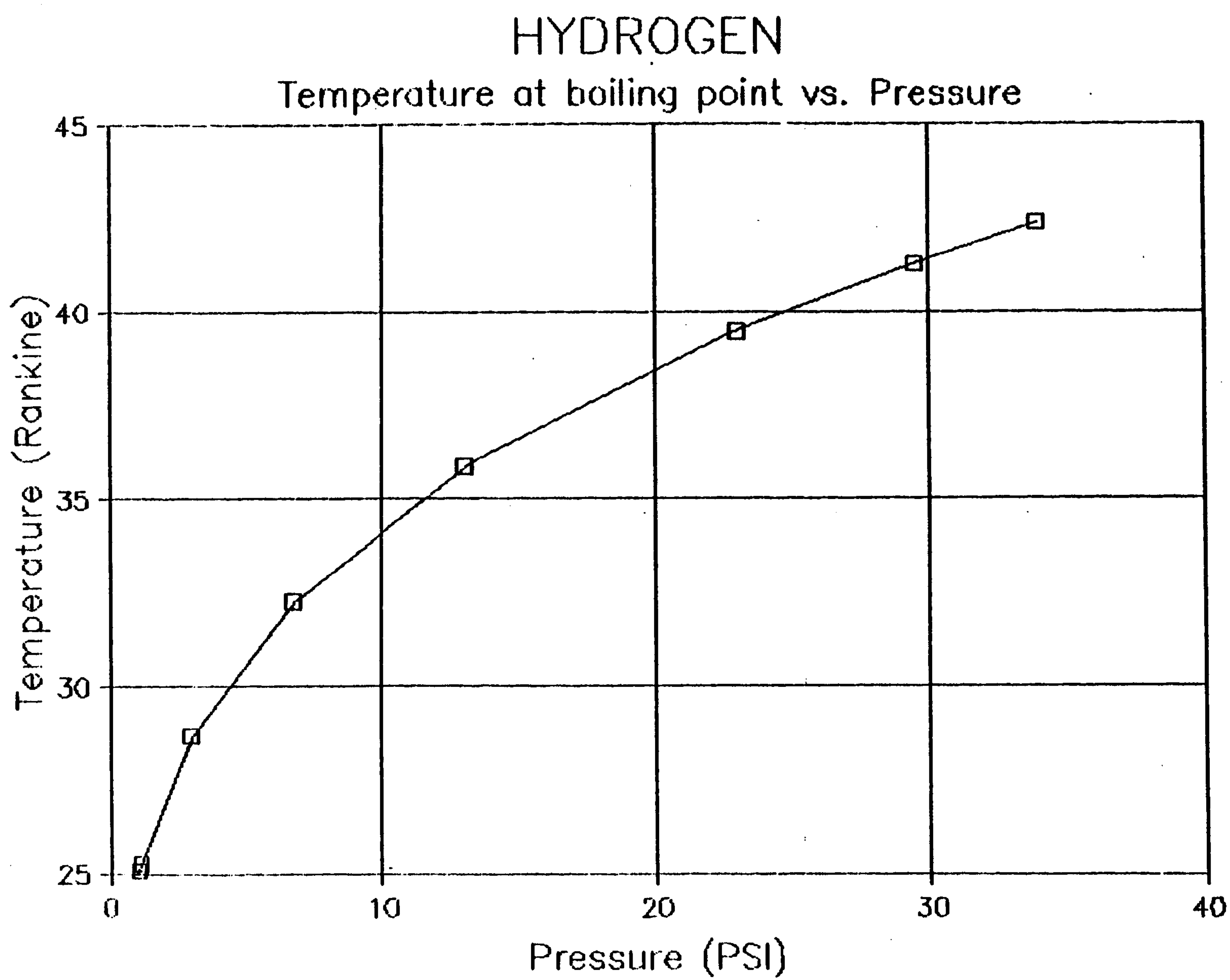
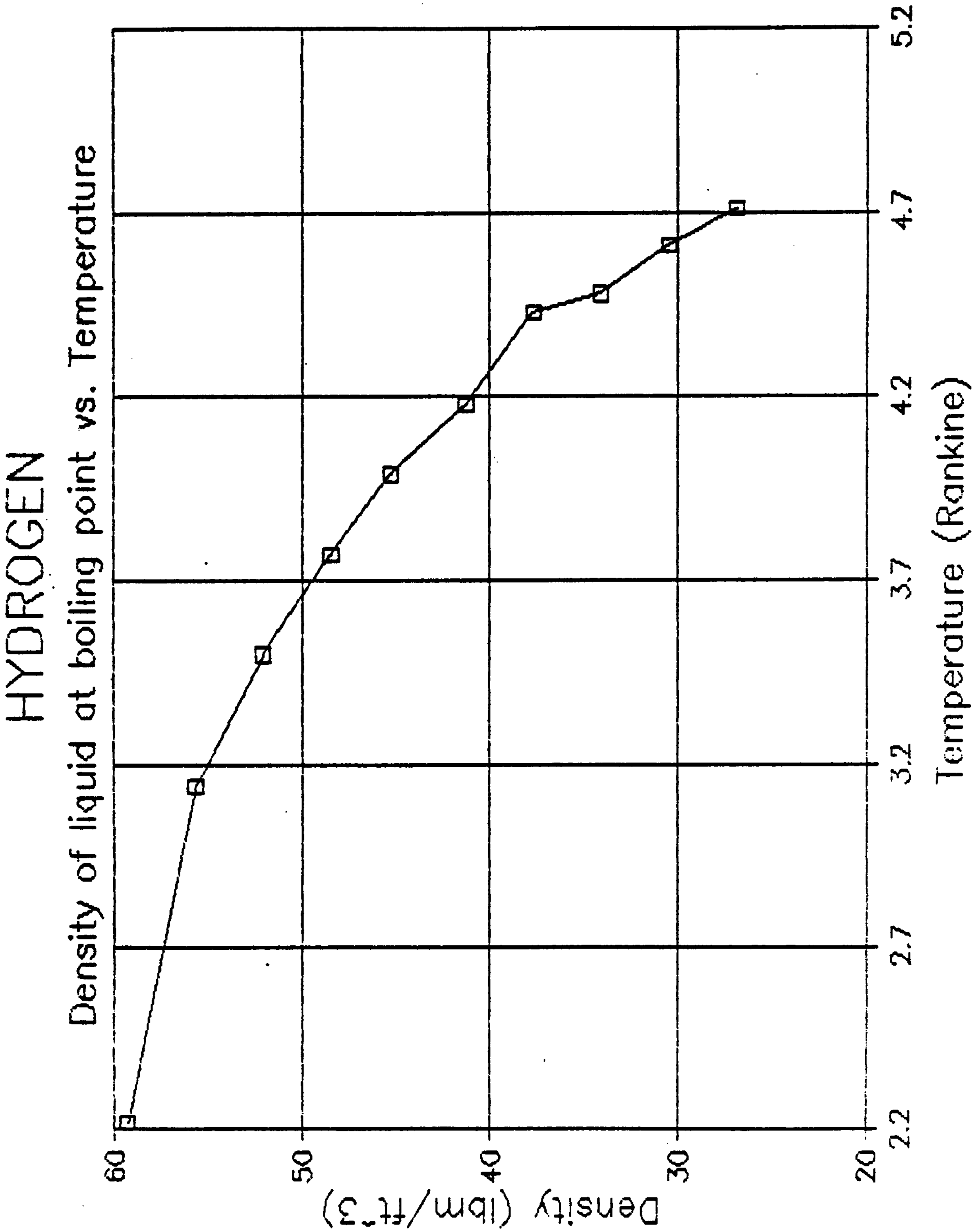
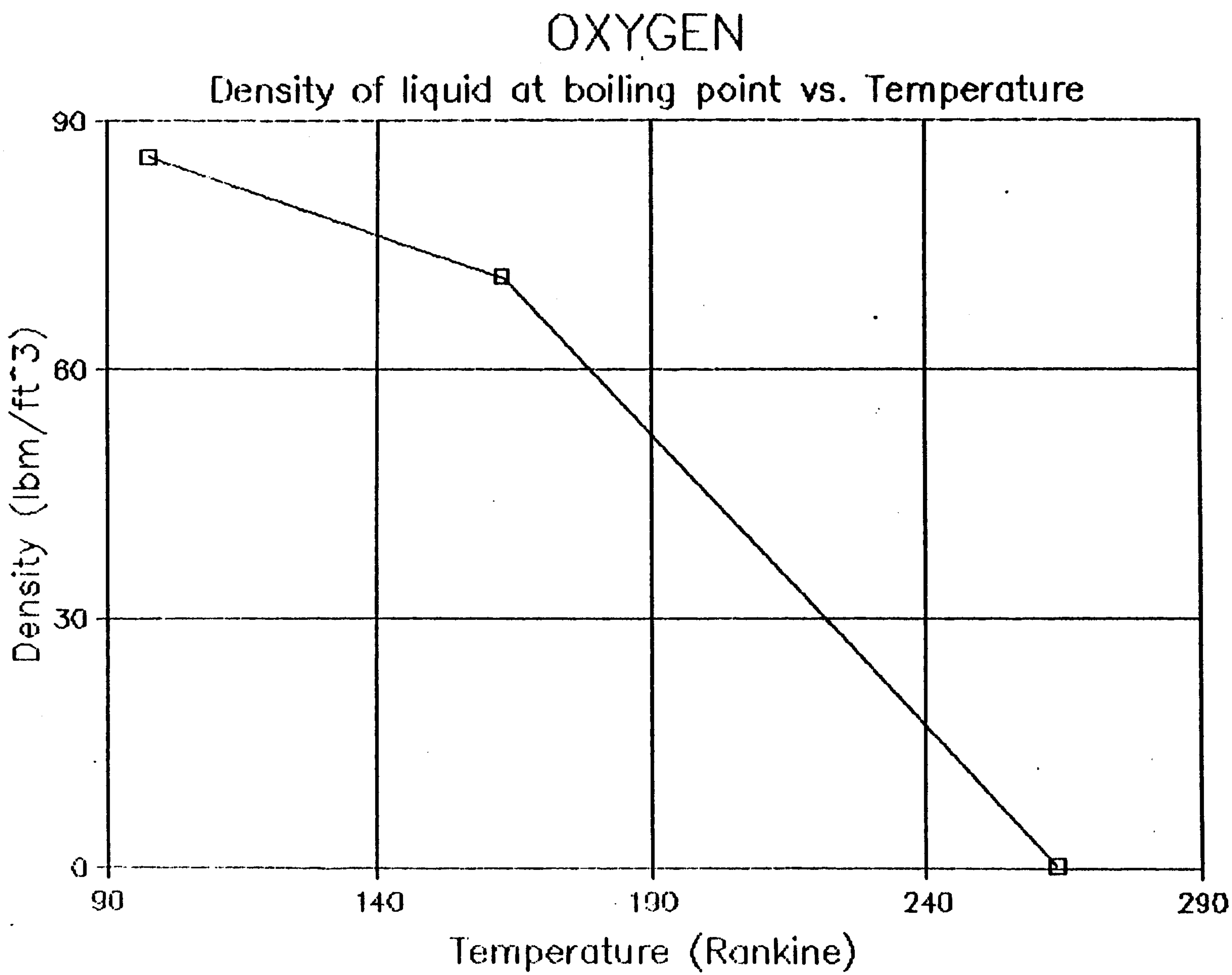
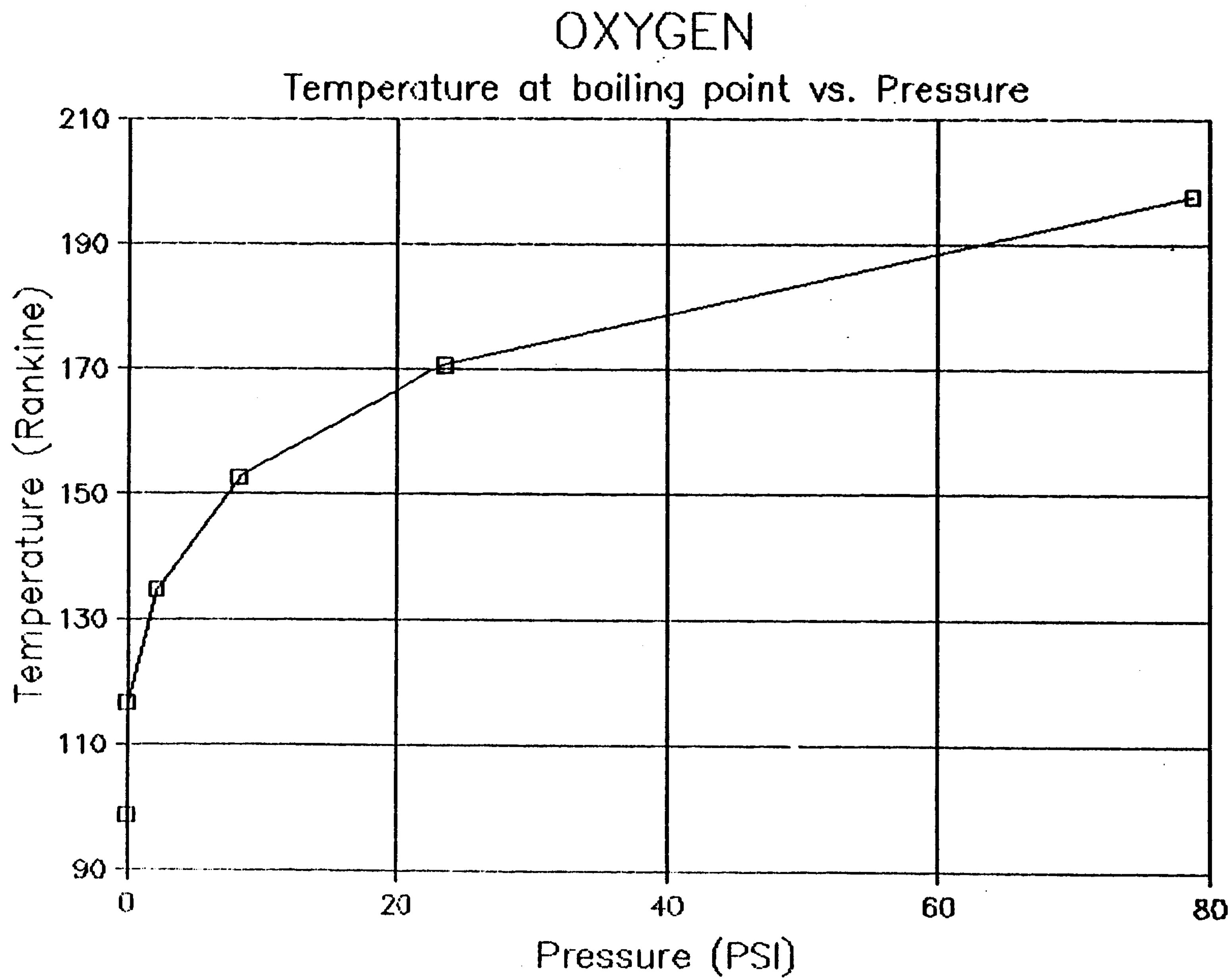
```
8000 OPEN"O",#1,"FUEL.DAT"
8010 FOR X=1 TO 3
8020 FOR Y=1 TO N(X,1):PRINT#1,PFUEL(X,Y),TPFUEL(X,Y):NEXT Y
8030 FOR Y=1 TO N(X,2):PRINT#1,RFUEL1(X,Y),TRFUEL(X,Y):NEXT Y
8040 FOR Y=1 TO N(X,3):PRINT#1,THVAPOR(X,Y),HVAPOR1(X,Y):NEXT Y
8050 NEXT X
8060 CLOSE#1
```

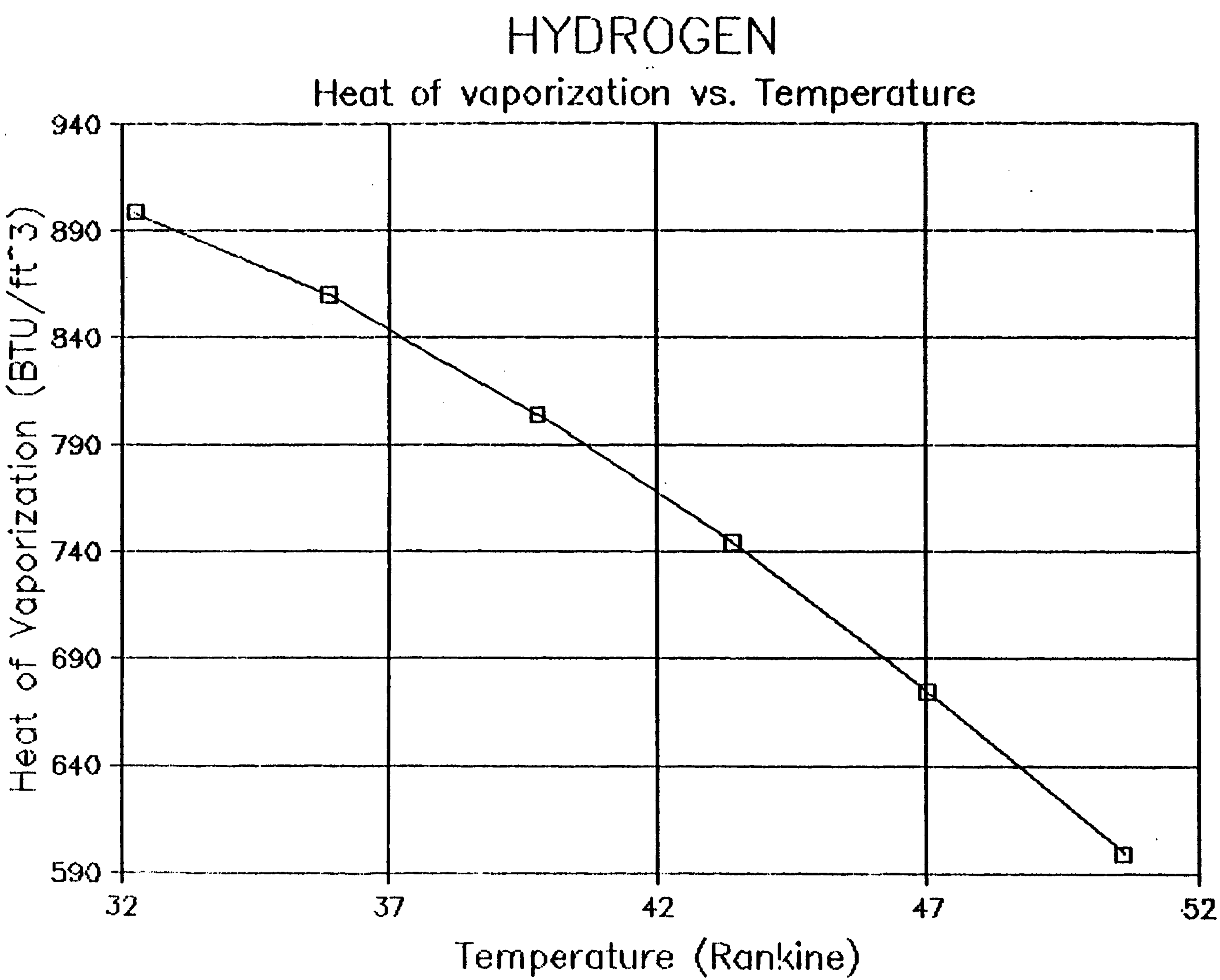

HYDROGEN
Temperature at boiling point vs. Pressure
Temperature (Rankine)
Pressure (PSI)
45
40
35
30
25
0
10
20
30
40



HYDROGEN
Density of liquid at boiling point vs. Temperature
Density (lbm/ft^3)
60
50
40
30
20
Temperature (Rankine)
2.2
2.7
3.2
3.7
4.2
4.7
5.2


OXYGEN
Density of liquid at boiling point vs. Temperature
90
60
30
0
Density (lbm/ft^3)
90
140
190
240
290
Temperature (Rankine)


OXYGEN
Temperature at boiling point vs. Pressure
Temperature (Rankine)
210
190
170
150
130
110
90
0
20
40
60
80
Pressure (PSI)


HYDROGEN
Heat of vaporization vs. Temperature
Heat of Vaporization (BTU/ft^3)
940
890
840
790
740
690
640
590
32
37
42
47
52
Temperature (Rankine)

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